CERN Summer Student Programme at the H-Beam, ASACUSA

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1 Introduction

The ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons) collaboration opperates experiments at the Antiproton Decelerator (AD) at CERN. One of the goals is testing of CPT symmetry breaking by investigating the Ground State Hyperfine Splitting (GS-HFS) of antihydrogen ($\bar{H}$), and comparing to that of hydrogen (H). The experiments are undertaken at the H-Beam and H-Bar experimental areas respectively and are both based on the Rabi-Spectroscopy method, but adapted for the respective experimental requirements. Being involved with the H-Beam experiment I will focus this report on the measurements undertaken on hydrogen, of which the aim is to measure the resonance frequencies of the Sigma (σ_1) and Pi (π_1) transitions within zero magnetic fields, an extension of the Ph.D. project of Martin Diermaier [1].

2 H-Beam

2.1 Beamline Preparation

Ultra-High Vacuum conditions are necessary for the measurements that are being undertaken at the H-Beam experiment, requiring pressures $<5\text{x}10^{-10}$ mbar. To achieve this, careful assembly of the beamline is required to ensure as minimal residue within the pipe. However baking of the beamline is undertaken with temperatures up to 120°C for the removal of any such residual gases and particles.

Furthermore, leak tests were performed by exposing external vacuum flanges and connections to helium and monitoring the content within the vacuum chambers. Helium was chosen due to the lack of abundance within the air, and thus within the beampipe. Therefore any detectable increase of helium would be due to gas exposed externally and corresponding to an inadequate vacuum assembly, of which was discovered and rectified.

Prior to any hydrogen measurements, argon gas was pumped through the experiment, and by selecting the appropriate mass of argon in the Quadrupole Mass Spectrometer (QMS) confirmation of the transport of gas through the beamline was able to be acquired, as a preliminary check of the beam's alignment.

2.2 Beamline Optimisation

Focussing of the hydrogen is accomplished by multiple sextupole magnets, of which is described in greater detail in Section 3.1. Simulations of the transport of hydrogen provide a optimised location in which the sextupole magnets can be positioned for the resonance measurements to provide the greatest count rate. Additional optimisation can be undertaken by movement of the coldhead to move the beam in the perpendicular x and y axis's. In addition to movement of the QMS to locate the focus spot of the beam. Carefully altering and optimising these parameters provided on average a count rate of 1000Hz, from which a clean and reliable resonance measurement was able to be measured.

2.3 Resonance Measurements

The H-Beam experiment is based upon a Rabi-spectroscopy set-up of which investigates the ground state hyperfine splitting of hydrogen. The splitting is a consequence of the coupling of the angular momenta and the corresponding magnetic momenta of the electron and proton, and within an external magnetic field produce four possible states. These states, depicted in Figure 1 are able to be classified into two groups, Low-Field Seekers (LFS) of which move in the direction of lower magnetic field regions and High-Field Seekers (HFS) which move in the direction of high magnetic field regions.

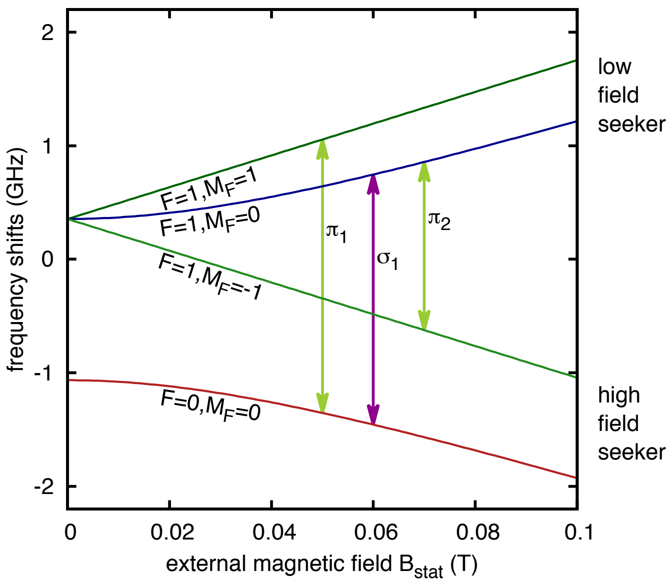

Figure 1: Breit-Rabi Diagram depicting the hyperfine splitting of hydrogen in an external magnetic field.

Sextupole magnets are used to defocus the HFS in order to produce a polarised hydrogen beam. Spin-flips of the remaining LFS are driven by microwave frequencies over a broad bandwidth through a cavity, subsequently causing a significant fraction of the LFS to 'spin-flip' to HFS of which are defocused by another set of sextupole magnets. Monitoring the frequency scan and the counts from the QMS a resonance frequency for the Sigma (σ_1) and Pi (π_1) transitions is able to be inferred from the dip of counts due to the hydrogen being spin-flipped and defocused.

Preliminary measurements were undertaken within the earth's magnetic field of which was monitored and the frequency shift accounted for. Overnight measurements for both the Sigma and Pi transitions were repeated and clear signals were acquired, Figures 2 and 3.

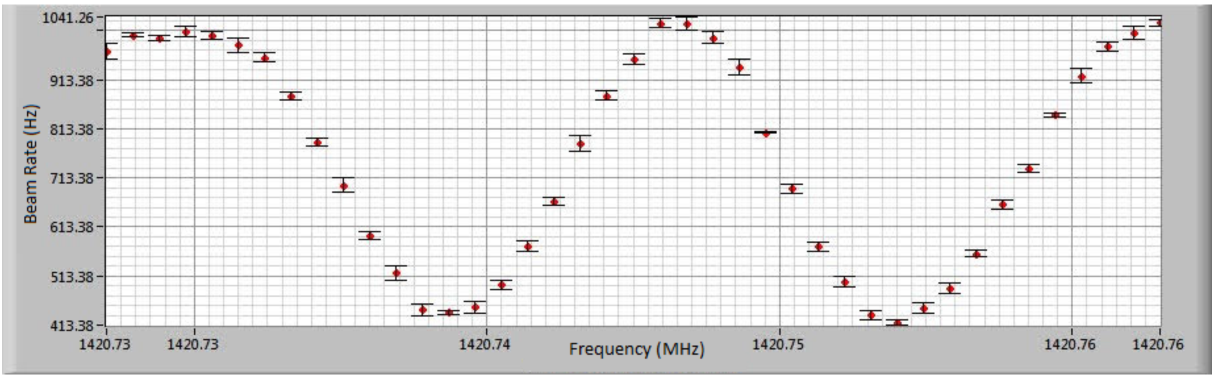

Figure 2: Pi resonance displaying the drop of beam count rate as a function of Frequency.

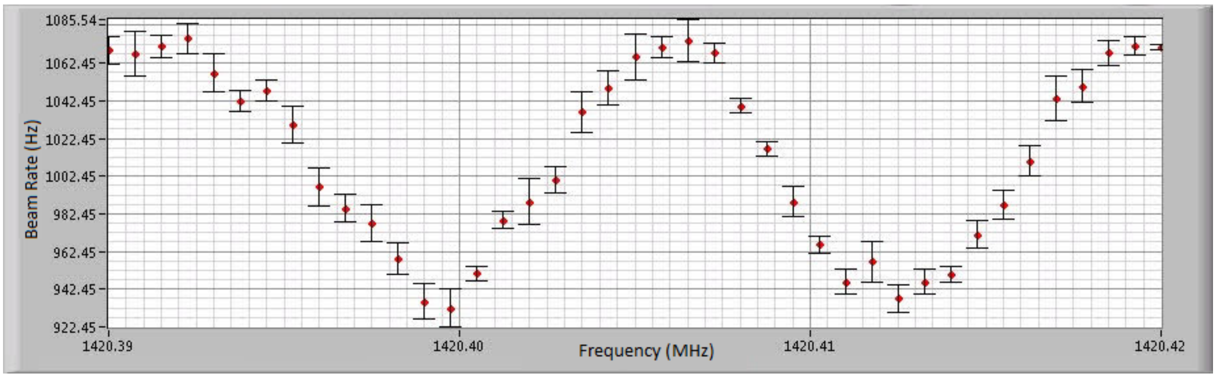

Figure 3: Sigma resonance displaying the drop of beam count rate as a function of Frequency.

3 Sextupole Magnets

3.1 Introduction

Sextupole magnets are used to focus the *LFS* and defocus the *HFS*, this requirement dictates the necessary magnetic field for the experiment. Ideally a zero magnetic field is present throughout the middle of the magnet, and an increasing magnetic field gradient radially outward.

Previous experiments undertaken at the H-Beam used the superconducting sextupole of the ASACUSA H-Bar GS-HFS spectrometer, however this is now in operation with the H-Bar set-up in the AD. An alternative of permanent magnets was opted for since it provided a more cost-effective solution in addition to providing greater control of the optimisation of the hydrogen beam count, due to the reduced size.

The sextupole is constructed in a multi-pole configuration of 12 permanent magnets, 50x15x15 mm^3 formed of a NdFeB compound. Characterisation of individual permanent magnets was undertaken by measuring the magnetic field on the surface of the two poles of the magnet. By comparing the average magnetic field strength per magnet and comparing this to the average of all 60 available, a relative field strength calculation was able to be undertaken. Furthermore a measure of the homogeneity was undertaken, this compared each individual measurement to an average, and the variation, measured by the standard deviation, provided a measurement of the profile of each magnet. Plotting these two parameters allowed similar magnetic field strengths and homogeneity magnets to be grouped together, Figure 4

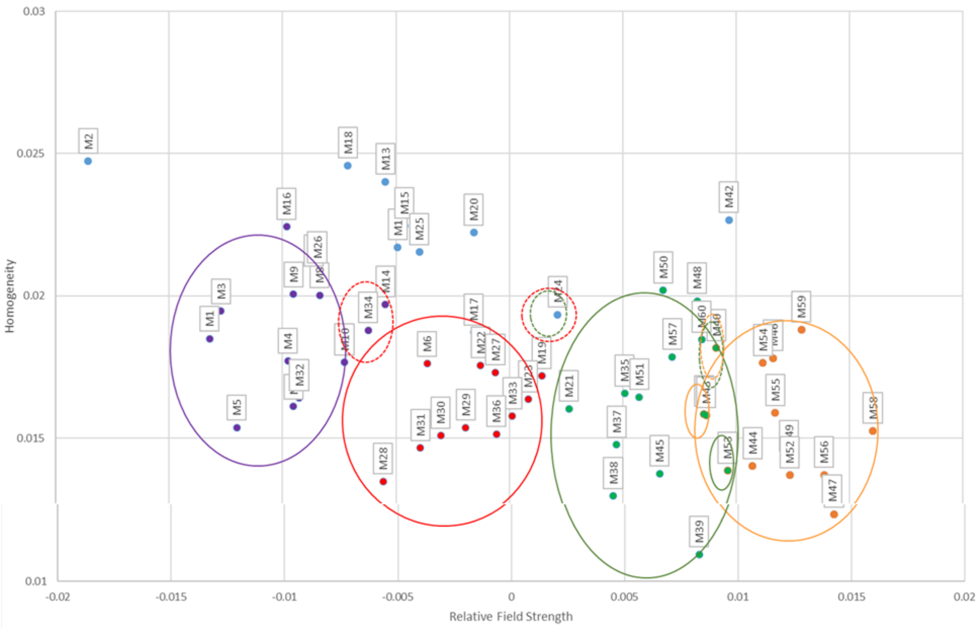

Figure 4: Analysis of the 60 permanent magnets of which are organised to form sextupole magnets D (Blue), E (Red), F (Green) and G (Yellow).

Simulations and various design processes proved a Halbach array configuration for the multi-pole sextupole magnets provides all of the necessary requirements for the magnet, Figure 5. Characterisation of the Halbach magnets was performed using a Gauss Meter of which was controlled by Arduino boards, from which a 3D map of the magnet was constructed and further analysed.

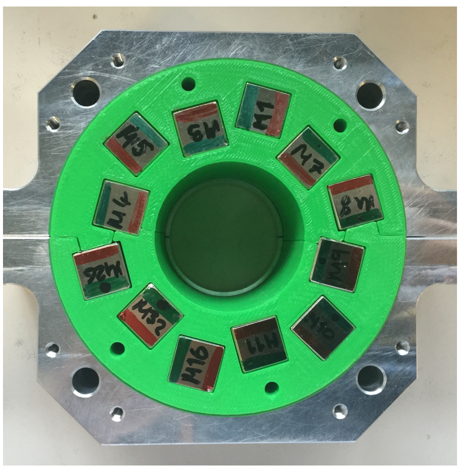

Figure 5: Halbach array configuration of the sextupole magnets for the H-Beam experiment.

3.2 Analysis

Measurements of the magnets were repeated in all four orientations, +x, +y, -x and -y. The advantage of this ensures that the background field is cancelled and any position offsets are also averaged, a Python script was created to calculate the average of these duplicated magnetic field measurements.

Absolute Magnetic Field, |B(r)| takes into consideration the two axis planes with the relationship, ${B_x}^2 + {B_y}^2 = |B(r)|$. Furthermore, the absolute magnetic field strength is related to the radial position within the sextupole magnet with the equation,

$$|B(r)| = \frac{Gs}{2} r^2 \tag{1}$$

Gs is a parameter of which is able to singularly parametrise the sextupole magnets. A linear trend can be fit to a plot of |B(r)| vs r^2 (Figure 6) and a relationship throughout the magnet can be investigated by analysing all of the Z-slices that were measured and fitting was undertaken with a modified Gaussian equation, (Figure 7)

$$Gs = a \cdot e^{(\frac{z-\mu}{\sigma})^2} \cdot ((z-\mu)^2 + b) \tag{2}$$

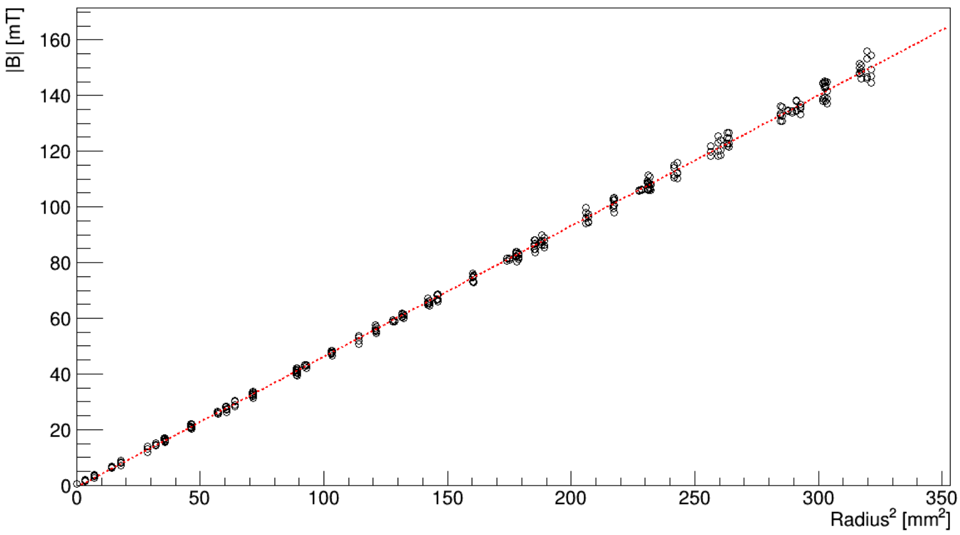

Figure 6: Calculation of Gs through a Z-Slice of Magnet D using Equation 1.

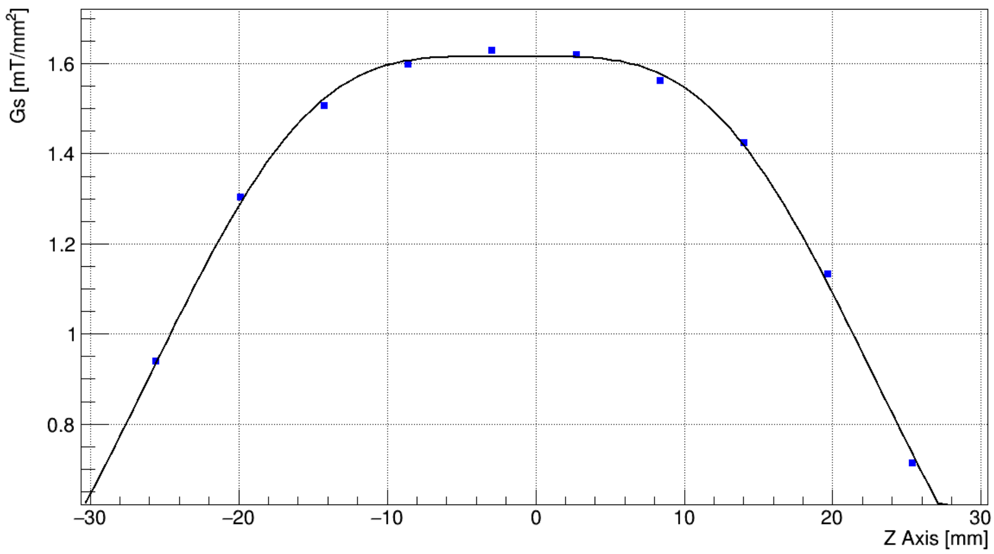

Figure 7: Gs beam profile through Magnet D fitting undertaken by Equation 2.

Additional parameters from this can be calculated, such as: G'dl by integrating the fit-function (Equation 3), L^{Eff} (Equation 4) and Gs^{Eff} (Equation 5) where ΔL is the length of the sextupole magnet (50mm). This method of characterisation is only truly valid for infinitely long sextupoles due to boundary effects, however as a first approximation these parameters provide additional characterisation and labelling of the multiple sextupole magnets used for the H-Beam experiment.

$$G'dl = \int_{-\infty}^{+\infty} Gs\, dz \tag{3}$$

$$L^{Eff} = \frac{G'dl}{G^{Max}} \tag{4}$$

$$Gs^{Eff} = \frac{G'dl}{\Delta L} \tag{5}$$

3.2.1 Minimum Field Co-ordinates

3D contour plots were built up from the Z-slices of the sextupole magnets from the measurements taken. From this a paraboloid in the form of equation 6 is capable to be fit. Gs parameter is fixed within this equation, and used from previously calculating the values. This method was chosen because it provided a more accurate method of fitting as opposed to leaving the parameter free where it was susceptible to inaccurate and incorrect fittings.

Of main interest in the fitting was the x_0 and y_0 parameters, these provided co-ordinates in which the magnetic field was minimum within the sextupole slice. This is expected to be (0mm, 0mm) along the central axis, Table 1. Additionally, the curvature of the field in the xy and yx axis's was calculated from the a and b parameters respectively. The curvature was expected to be 1, circular, and consistently throughout the calculations proved to be so.

$$|B(r)| = \frac{Gs}{2}\left(\left(\frac{x-x_0}{a}\right)^2 + \left(\frac{y-y_0}{b}\right)^2\right) \tag{6}$$

3.2.2 Results

ID	*G'dl* [mT/mm]	Gs^{Eff} [mT/mm^2]	L^{Eff} [mm]	Y_0 [mm]	X_0 [mm]	*a*	*b*
A	84.15	1.68	52.84	-0.0191±0.0003	-0.0065±0.0003	1.0039±0.0003	1.0015±0.0005
B	84.10	1.68	53.36	0.00319±0.0057	-0.0017±0.0058	1.0027±0.0005	0.9981±0.0005
C	84.24	1.68	53.10	-0.0545±0.0066	0.0416±0.0066	1.0301±0.0006	1.0362±0.0006
D	85.80	1.72	53.08	0.0547±0.0040	0.0412±0.0037	1.0003±0.0003	1.0067±0.0003
E	86.09	1.72	53.08	0.0076±0.0036	0.0170±0.0036	1.0055±0.0003	0.9995±0.0003
F	86.00	1.72	53.02	-0.1096±0.0045	-0.0987±0.0046	1.0067±0.0004	1.0005±0.0004
G	86.03	1.72	53.00	-0.0387±0.0041	0.0769±0.0042	1.0045±0.0003	1.0020±0.0003
H	83.49	1.67	53.04	0.0133±0.0037	-0.0273±0.0036	0.9969±0.0003	1.0084±0.0003
I	84.14	1.68	52.96	0.1508±0.0062	-0.2192±0.0063	1.0060±0.0005	1.0007±0.0005

Table 1: Complete characterisation of the nine sextupole magnets of which will be used on the H-Beam experiment.

4 Conclusions

During my summer working with the ASACUSA group I have learnt and developed a multitude of skills, most notably working with an ultra-high vacuum for the H-Beam experiment. This required learning the necessary procedures to safely and successfully maintain such a vacuum, of which in the end resulted in measurements of the Sigma (σ_1) and Pi (π_1) ground state hyperfine splitting resonances within the earth's magnetic field. In addition to learning the procedures of efficiently operating the hydrogen beam and operating the microwave cavity as well as the detection of the hydrogen with the aid of the QMS. Furthermore, characterisation of the Halbach sextupole magnets was undertaken, this provided verification of the magnetic beam profile to be minimal along the central axis. Additionally, these measurements will provide characterisation of the magnets to be used for the experiment, as well as the possibility of improving future simulations of transport of the hydrogen beam.

References

[1] Diermaier, M. *Determination of the hydrogen ground-state hyperfine splitting in a beam and perspectives for antihydrogen* (2016)
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